

WHAT IS THE SHELL AROUND R CORONAE BOREALIS?

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ABSTRACT

The hydrogen-deficient, carbon-rich R Coronae Borealis (RCB) stars are known for being prolific producers of dust which causes their large iconic declines in brightness. Several RCB stars, including R CrB, itself, have large extended dust shells seen in the far-infrared. The origin of these shells is uncertain but they may give us clues to the evolution of the RCB stars. The shells could form in three possible ways. 1) they are fossil Planetary Nebula (PN) shells, which would exist if RCB stars are the result of a final, helium-shell flash, 2) they are material left over from a white-dwarf merger event which formed the RCB stars, or 3) they are material lost from the star during the RCB phase. Arecibo 21-cm observations establish an upper limit on the column density of H I in the R CrB shell implying a maximum shell mass of $\lesssim 0.3 M_{\odot}$. A low-mass fossil PN shell is still a possible source of the shell although it may not contain enough dust. The mass of gas lost during a white-dwarf merger event will not condense enough dust to produce the observed shell, assuming a reasonable gas-to-dust ratio. The third scenario where the shell around R CrB has been produced during the star's RCB phase seems most likely to produce the observed mass of dust and the observed size of the shell. But this means that R CrB has been in its RCB phase for $\sim 10^4$ yr.

1. INTRODUCTION

R Coronae Borealis (R CrB) is the prototype for its eponymous class of stars, which are very rare and have many unusual characteristics including extreme hydrogen deficiency and large, sudden declines in brightness of 8 magnitudes or more (Lambert & Rao 1994; Clayton 1996, 2012). These declines are caused by clouds of carbon dust forming near the atmospheres of the stars, which are later dissipated by radiation pressure. Only about 100 R Coronae Borealis (RCB) stars are known in the Galaxy. Therefore, these stars may be the result of a rare form of stellar evolution or are in an evolutionary phase that lasts only a short time.

Two scenarios have been suggested for producing an RCB star: the double degenerate (DD) and the final helium-shell flash (FF) models (Iben et al. 1996; Saio & Jeffery 2002). In the DD model, an RCB star is the result of merger between a CO- and a He-white dwarf (WD) (Webbink 1984). The derivation of CNO isotopic ratios (in particular the excess of ^{18}O) in RCB stars favors the DD scenario for these stars (Clayton et al. 2005, 2007; García-Hernández et al. 2009, 2010). In the FF model, a star evolving into a white dwarf undergoes a final helium-shell flash and expands to supergiant size (Fujimoto 1977). In this scenario, the star may have recently gone through a planetary nebula (PN) phase. Three stars (Sakurai's Object, V605 Aql, and FG Sge) have been observed to undergo FF outbursts that transformed them from hot evolved stars into cool giants with spectroscopic properties similar to RCB stars (Clayton & De Marco 1997; Gonzalez et al. 1998; Asplund et al. 1998, 1999, 2000; Clayton et al. 2006). These FF stars are all surrounded by PNe.

Several RCB stars have extended dust shells that are seen in reflected light in the visible or in emission from the far-IR (e.g., Schaefer 1986; Walker 1985, 1986; Bright et al. 2011). Infrared spectroscopy of RCB stars has been possible thanks to the Infrared Space Observatory (ISO) and the *Spitzer* Space Telescope, which has permitted the extraction of the characteristics of the IR emitting dust shell around RCBs (Lambert et al. 2001; García-Hernández, Rao & Lambert 2011a,b, 2013). It has been suggested that the mass loss in R CrB and V854 Cen is bipolar (Rao & Lambert 1993; Clayton et al. 1997). This geometry is very common in PNe (Balick & Frank 2002). Further, the nebulosity, including cometary knots, seen around R CrB and UW Cen has similar morphology to a PN shell (Clayton et al. 2011, Clayton et al. 2015, in preparation). In this paper, we investigate whether the shell around R CrB is consistent with the scenarios suggested for the evolution of the RCB stars.

2. ARECIBO 21-CM OBSERVATIONS

Radio observations containing the region around R CrB have been obtained from the first data release (DR1³) Galactic Arecibo L-band Feed Array H I (GALFA-HI) Survey (Peek et al. 2011). The GALFA-HI survey provides both high resolution ($4'$) and high sensitivity (typical rms ~ 80 mK) due to their 305-m aperture and the installation of the Arecibo L-band Feed Array (ALFA) (Peek et al. 2011). Fully reduced “narrow” and “wide” band data cubes were retrieved from the survey. The former provided 0.18 km s^{-1} resolution in the local standard of rest (LSR) in the range $v_{\text{LSR}} = \pm 190 \text{ km s}^{-1}$, while the latter provided 0.74 km s^{-1} resolution in the range $v_{\text{LSR}} = \pm 750 \text{ km s}^{-1}$. A full description of the data acquisition, which includes both drift and basketweave scanning, and reductions for the GALFA-HI survey are presented by Peek et al. (2011) (see their §3 and §4, respectively).

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3. ORIGIN OF THE R CRB DUST SHELL

3.1. The R CrB Dust Shell

The foreground extinction toward R CrB is quite small, $E(B-V) \sim 0.035$ mag, since it lies at high Galactic latitude ($b^{\text{II}} = +51^\circ$) (Schlegel et al. 1998; Schlafly & Finkbeiner 2011). At maximum light, R CrB is $V=5.8$ mag and $B-V=0.6$ mag (Lawson et al. 1990). Based on the absolute magnitude/effective temperature relationship found for the Large Magellanic Cloud RCB stars, the absolute magnitude of R CrB is estimated to be $M_V = -5$ mag (Alcock et al. 2001; Tisserand et al. 2009). For the analysis in this paper, we thus adopt a distance to R CrB of 1.4 kpc. The large extended far-IR shell, with a radius of $\sim 10'$, surrounding R CrB was discovered with *IRAS* and then studied further with the *Spitzer* and *Herschel* telescopes (Gillett et al. 1986; Clayton et al. 2011; García-Hernández, Rao & Lambert 2011b, 2013). At the assumed distance of R CrB, the radius of the shell corresponds to 4 pc. Monte Carlo radiative transfer modeling of the R CrB shell suggests that it contains $10^{-2} M_\odot$ of dust (Clayton et al. 2011).

3.2. A Planetary Nebula Shell?

The PNe around the FF stars, V605 Aql, Sakurai's Object, and FG Sge are still ionized. The shell around R CrB is not. There is a small subclass of RCB stars that are much hotter ($T_{\text{eff}} = 15,000\text{--}20,000$ K) than the typical RCB stars and are surrounded by PNe (Pollacco et al. 1991; De Marco et al. 2002). They are not hot enough at present to ionize their surrounding PNe, but the nebulae have not had time to recombine. The shells around the cooler RCB stars could be old PNe that have recombined. There are some strong similarities between the morphology of the shells of UW Cen and R CrB, and some PNe such as the Eskimo Nebula. Cometary features seen in PNe such as the Eskimo are similar to those seen in these two RCB stars (Clayton et al. 2011). The recombination time depends on the electron densities of the shells and could range from hundreds to thousands of years. If $n_e = 200 \text{ cm}^{-3}$, as assumed for Sakurai's Object, the recombination time for R CrB's PN shell would be ~ 380 yr (Pollacco 1999). The amount of time that R CrB has been an RCB star is unknown but it is one of the first variable stars to be discovered (Pigott & Englefield 1797), so we know that it has been in its RCB star phase for at least 200 yr.

The PNe seen around the FF stars, Sakurai's Object and V605 Aql, are thought to be $\sim 2 \times 10^4$ yr old, both with expansion velocities of $\sim 30 \text{ km s}^{-1}$ and radii of 0.35 pc for V605 Aql and 0.7 pc for Sakurai's Object (Pollacco et al. 1992; Guerrero & Manchado 1996; Pollacco 1999). A FF star may not be old enough to produce a PN shell of the size seen around R CrB as it only takes a few years for the star to reach its RCB-like phase after the FF (Herwig 2001).

If the R CrB shell is, in fact, a PN shell then it should be hydrogen rich (Gillett et al. 1986). No pointed 21-cm measurements of any RCB circumstellar shells have been published previously. A visual inspection of the narrow band GALFA-HI data cube through velocity space was performed to see if there were any obvious H I features. The search focused on $\pm 30 \text{ km s}^{-1}$ of the v_{LSR} of R CrB $\sim 37 \text{ km s}^{-1}$ (The barycentric radial velocity of R CrB

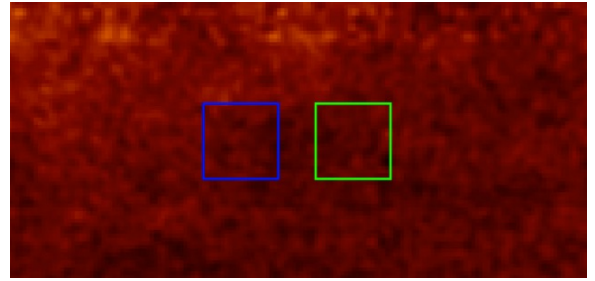


FIG. 1.— GALFA-HI field ($2^\circ 25' \times 1^\circ 15'$) showing the location of the R CrB shell (green square) and the area used for background subtraction (blue square). The squares are $20' \times 20'$.

$\sim 22.3 \text{ km s}^{-1}$ (Lawson & Cottrell 1997)). No obvious structure was discerned.

Next, a $20' \times 20'$ square region, roughly the size of the dust shell, centered on R CrB was selected, as well as a background region of the same size as shown in Figure 1. The background reference spectrum were subtracted from the spectrum toward the R CrB shell to determine if there is any H I emission that might be associated with the shell. While fluctuations in the background H I limit the comparison in many directions, one reference position, shown in Figure 1, has an H I spectrum that is identical within the noise to the spectrum averaged over the shell at the relevant velocities, and the difference spectrum (Figure 2) can be used to limit the H I mass of R CrB.

The rms noise (σ_{rms}) in the 0.18 km s^{-1} channels of Figure 2 is 27 mK. Over a $\pm 30 \text{ km s}^{-1}$ interval, this gives a 3σ limit on column density, N_H (atoms cm^{-2}) in the R CrB shell of 4.9×10^{17} . This was derived using $N_H = 3.0 \times 1.82 \times 10^{18} \times \sigma_{\text{rms}} \times dv \times \sqrt{n_{\text{ch}}}$, where dv is the 21cm channel spacing (0.18 km s^{-1}) and n_{ch} is the number of channels (~ 330) over the relevant velocity range (Dickey & Lockman 1990). The mass of any neutral hydrogen, in solar masses, is then less than $M_H = 6.9 \times 10^{-28} \times N_H \times D^2 \times \Omega$, where D is the distance in pc (1400 pc), and Ω is the solid angle of the region in arcmin^2 . With our upper limit on N_H , the corresponding 3σ limit on H I in the R CrB shell is $0.3 M_\odot$. Assuming that the mass loss is contained in a shell that has been moving outward at 30 km s^{-1} , the PN shell would take $\sim 10^5$ yr to expand to $r = 4$ pc. A shell of that age would almost certainly have had time to recombine and become neutral.

The number density of H in this shell would be low, similar to that seen in the diffuse interstellar medium. Therefore, the fraction of H_2 will be near zero, and all of the H will be atomic and neutral (Rachford et al. 2009). The 21-cm measurements presented here put a strong upper limit on the H mass in the R CrB shell. A study of the gas and dust masses in the shell of the PN, NGC 6781, gives a total shell mass of $0.86 M_\odot$ and a dust mass of $4 \times 10^{-3} M_\odot$ and therefore a gas-to-dust ratio of about 215 (Ueta et al. 2014). Assuming a gas-to-dust ratio of 200, the amount of dust in the R CrB shell would be $\lesssim 10^{-3} M_\odot$.

3.3. Mass Loss from a White Dwarf Merger?

We have simulated the RCB DD formation scenario by running three binary WD merger models using our fully three-dimensional adaptive mesh refinement (AMR)

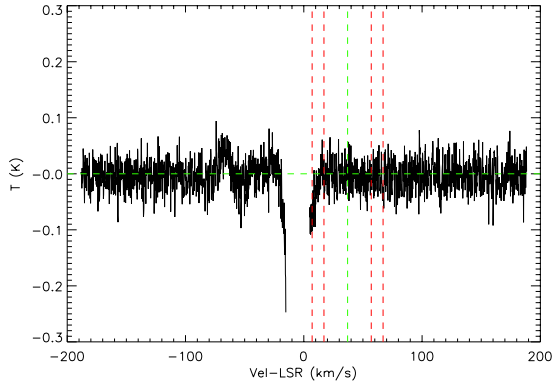


FIG. 2.— A background-subtracted temperature vs. radial velocity plot for area around R CrB. The vertical green dashed line is the position of R CrB in radial velocity and the two vertical red lines mark ± 20 and ± 30 km s^{-1} from the velocity of R CrB. The feature at -70 km s^{-1} is part of a large elongated emission not associated with the R CrB shell. The horizontal green dashed line is at temperature = 0° .

code (Marcello & Tohline, in prep). This code evolves density, total energy, and angular, vertical, and radial momenta on a rotating Cartesian mesh. Once started, the model is driven into closer contact by artificially removing angular momentum from the system at a rate of 1% per orbit for several orbits. Through AMR, we are able to run the models in large grids whose box dimensions are 20–30 times larger than the orbital separation. This allows for a more accurate determination of mass loss from the system than on a smaller grid, where much of the material exiting the grid does not possess enough energy to escape. The initial conditions were created using the self-consistent field technique (SCF) to create a detached synchronously rotating binary WD in equilibrium just shy of becoming semi-detached (Hachisu 1986; Even & Tohline 2009). Each model run follows the merger of a CO- and a He-WD in a close binary orbit. The $q=0.8$ and $q=0.5$ models have a hybrid CO/He accretor, which as described by Staff et al. (2012) is a WD with a CO core and a He envelope of about $0.1 M_\odot$. The results, along with the initial conditions, of our simulations are summarized in Table 1.

In the models presented here between 0.9 and 3.3% of the initial mass escapes and is not expected to fall back onto the new merged star. Therefore, in the three models described in Table 1 the mass lost from the two WDs, which could form into a circumstellar shell around the new RCB star, is $\sim 10^{-2} M_\odot$. The gas that has escape velocity is $>95\%$ He so a maximum of 5% of the gas could condense into dust. Assuming this and a different gas-to-dust ratio of 100 (Whittet 2003), the amount of dust in such a shell would be $\sim 5 \times 10^{-6} M_\odot$. A different gas-to-dust ratio was adopted, since in this scenario the envelope is not PN-like. The merger event itself only takes a few minutes after which there is a rapid expansion to supergiant size (Staff et al. 2012). Zhang et al. (2014) estimate that the new star will expand to $\sim 200 R_\odot$ in 500 yr. The estimated velocities of the gas escaping the grid in the simulations listed in Table 1 is 600–900 km s^{-1} . This gas would take $\sim 10^4$ yr to expand to the size of the R CrB shell. These velocities are the same order

TABLE 1
MODEL RESULTS

Parameter	Model 1	Model 2	Model 3
Mass Ratio (q)	0.51	0.70	0.80
Accretor Mass (M_\odot)	0.503	0.526	0.561
Donor Mass (M_\odot)	0.255	0.366	0.45
Total Mass (M_\odot)	0.758	0.892	1.011
% Mass Lost	2.3	0.90	3.3
Initial Period (s)	181	118	90.9
Final/Initial Period	9.9	2.9	6.9
Initial separation (R_\odot)	6.30×10^{-2}	5.00×10^{-2}	4.38×10^{-2}
Grid Box Dim. (R_\odot)	1.74	1	1.38
Orbits driven at 1%	2.5	4	2.5
dx (R_\odot)	5.66×10^{-4}	6.51×10^{-4}	4.49×10^{-4}
Init. Sep. in Cells	111	77	98

TABLE 2
SHELL TYPES

Type	v_{exp} (km s^{-1})	Time (yr)	Dust Mass (M_\odot)	Total Mass (M_\odot)
Planetary Nebula	30	10^5	$<10^{-3}$	<0.3
WD merger	600–900	10^4	5×10^{-6}	10^{-2}
RCB star	400	10^4	$>10^{-3}$...

of magnitude as the winds measured in RCB stars in the He I $\lambda 10830$ line (Clayton et al. 2013). This analysis assumes that any PN/common envelope phases of the two stars in the binary occurred long before the merger but this time period is not known.

3.4. RCB Phase Mass Loss?

It is thought that dust forms in puffs near the atmosphere of an RCB star (Clayton 1996). We adopted the assumption that during a single dust formation event a puff forms at $2 R_\star$ ($R_\star = 85 R_\odot$) and subtends a fractional solid angle of 0.05, which results in the photosphere of the star being obscured and a dust mass of $\sim 10^{-8} M_\odot$ (Clayton et al. 1992, 2011). Declines occur when a puff forms along the line of sight, but other puffs are likely forming around the star that do not cause declines. These puffs can be detected in the IR. Recent studies pertaining to IR variability of RCB stars has found that the covering factor can vary from RCB star to RCB star and find an average covering factor of 0.28 ± 0.04 for R CrB (García-Hernández, Rao & Lambert 2011b; Rao & Lambert 2015). Other studies find a higher covering factor (Hecht et al. 1984; Clayton et al. 1999). In addition, a correlation between pulsation phase and the timing of dust formation has been found in several RCB stars (Crause et al. 2007) and they typically show regular or semi-regular pulsation periods in the 40–100 d range (Lawson et al. 1990). R CrB, itself, does not have one regular period but has shown periods of 40 and 51 d (Fernie & Lawson 1993). Therefore, if a dust puff forms somewhere around R CrB every 50 days then $\sim 10^{-7} M_\odot$ of dust will form per year around the star.

There is strong evidence from observations at He I $\lambda 10830$ that the dust, once formed, is accelerated quickly

by radiation pressure from the star to $\sim 400 \text{ km s}^{-1}$ (Clayton et al. 1992, 2003, 2013). The He gas is likely dragged outward by the dust. Therefore, dust produced during the RCB phase could fill the R CrB shell in only $\sim 10^4 \text{ yr}$. In that time, R CrB will produce at least $10^{-3} M_{\odot}$ of dust depending how many puffs form around the star. Considering the assumptions made here and those made in the radiative transfer modeling, this estimated dust mass is close to the $10^{-2} M_{\odot}$ estimated by Clayton et al. (2011). The mass of gas in an RCB shell is unknown. The gas will be primarily He with little or no H.

The observed far-IR shell around R CrB appears nearly spherical. The suggestion that the present day mass loss from R CrB is bipolar would not support this morphology (Rao & Lambert 1993). Further polarimetric or interferometric observations are needed to determine the morphology of the RCB-star dust mass loss (e.g., Clayton et al. 1997; Bright et al. 2011).

4. SUMMARY

The estimated masses of the circumstellar shells in the FF/PN, WD merger (DD), and RCB scenarios are summarized in Table 2. If the shell is an old fossil PN in the FF scenario, then the gas should be H-rich. In the other two cases, it would be H-poor and dominated by He gas. The results of the 21-cm observations find no detectable H in the R CrB shell. The observations place upper limit of $\sim 0.3 M_{\odot}$ on the mass of the PN. The ionized masses observed for some PNe are in this range (e.g., Boffi & Stanghellini 1994; van Hoof & van de Steene 1999). The radius of R CrB shell is very large for PN shell. The PN shells of the FF stars, V605 Aql and Sakurai's Object, are 0.35 and 0.7 pc, respectively. A 4 pc radius PN shell would take $\sim 10^5 \text{ yr}$ to fill at 30 km s^{-1} . The gas mass loss in a WD merger is $\sim 10^{-2} M_{\odot}$. Since this gas is mostly He, little dust could form in such a shell.

The gas mass of the R CrB shell is not known, but the dust mass has been estimated to be $10^{-2} M_{\odot}$ (Clayton et al. 2011). If it formed during the RCB phase then the shell would be filled with He gas, the mass of which cannot be measured so the gas-to-dust ratio is unknown. Based on the analyses above, we would expect only $10^{-3} - 10^{-6} M_{\odot}$ of dust in the PN and WD merger mass loss scenarios. Thus the suggestion that the R CrB shell has formed from the dust forming during its present RCB phase seems most likely since it can form $\gtrsim 10^{-3} M_{\odot}$ of dust. If true, this model implies that R CrB has been an RCB star for $\sim 10^4 \text{ yr}$ to have produced a 4 pc radius shell. More sensitive 21-cm observations of RCB star shells are needed to place more stringent constraints on their H masses.

We thank the anonymous referee for thoughtful suggestions that have improved this paper. This study was supported by NSF CREATIV grant AST-1240655. This study utilized data from Galactic ALFA HI (GALFA H I) survey data obtained with the Arecibo 305m telescope. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under Cooperative Agreement with the NSF. The GALFA H I survey is funded by the NSF through grants to Columbia University, the University of Wisconsin, and the University of California. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation. Portions of this research were conducted with high performance computational resources provided by Louisiana State University (<http://www.hpc.lsu.edu>). This material is based upon work supported by the Louisiana Optical Network Institute (LONI). This program also used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1053575.

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